Journal of Computer Science and Artificial Intelligence
ISSN: 3078-8242 (Print), ISSN: 3078-2309 (Online) | Vol. 8, No. 2, 2026

Research on the Improvement Path of Security Governance Capability of Distribution Network Driven by Intelligent Technology

Yueru Liu, Minjing Li, Linying Sun *

Wenzhou Polytechnic University, Wenzhou, China

Abstract: This article proposes a systematic improvement path for the security governance capability of distribution networks driven by intelligent technology. Realize global state awareness through IoT sensors and edge computing; Based on AI algorithms for fault diagnosis and situation deduction, combined with digital twin platform optimization decision-making; Constructing self-healing control system based on intelligent terminal and virtual power plant technology. The technical level focuses on cloud-side collaborative architecture and deep learning algorithm, the management level promotes cross-departmental collaboration and process standardization, and the mechanism level improves the standard specification and dynamic evaluation mechanism. Taking a demonstration area as an example, after the implementation, the fault location time is reduced from 42 minutes to 2 minutes, the annual power outage events are reduced by 78%, and the voltage qualification rate is increased to 99.71%, which verifies the effectiveness of the closed-loop system of "perception-analysis-decision-execution". The research shows that the integration of intelligent technology, management innovation and institutional guarantee can improve the operation toughness and governance efficiency of distribution network.

Keywords: Intelligent technology, Security governance, Improvement path, Digital twin.

1. Introduction

With the acceleration of global energy transformation and the in-depth development of smart grid construction, the operation characteristics of distribution network, as a key link connecting transmission network and end users, are undergoing profound changes. On the one hand, the large-scale access of new loads, such as distributed power supply and electric vehicle charging piles, has transformed the distribution network from a traditional one-way power supply network to a complex active network with two-way power flow; On the other hand, users' requirements for power supply reliability, power quality and power consumption experience are increasing. Under this background, the safe and stable operation of distribution network has become an important cornerstone to ensure social and economic development and people's livelihood electricity demand.

Facing the increasingly complex network structure, the traditional security governance model of distribution network is facing severe challenges. For a long time, the security management of distribution network mainly depends on manual regular inspection, passive repair afterwards and simple protection strategy based on physical mechanism [1]. This governance model of "compartmentalization and focusing on the afterwards" has obvious lag and limitations. Due to the lack of sensing means, equipment hidden dangers and line faults are often difficult to find in time, leading to frequent "blind spots" [2]; With the rapid increase in the number of power grid equipment, there is a huge scissors gap between massive operation data and limited data processing capacity, which leads to the lack of data value mining and the difficulty in achieving accurate risk warning [3]; There is a dislocation between the rapid iteration of technical equipment and the lagging management mechanism, which restricts the overall improvement of governance efficiency.

Intelligent technology has the characteristics of comprehensive perception, efficient transmission, intelligent processing and accurate decision-making, which can give the distribution network the ability of "visibility, controllability and measurability". Based on this, this paper discusses the promotion path of security governance capacity of distribution network driven by intelligent technology. Through in-depth analysis of the empowerment mechanism of intelligent technology in distribution network security governance, a systematic promotion path covering technology, management and mechanism optimization is constructed, and its effectiveness is verified by practical cases. This study has important theoretical reference value and practical guiding significance for breaking the data barrier of distribution network security governance, improving the efficiency of fault handling and building a high-toughness modern distribution network.

2. Present Situation and Challenges of Distribution Network Security Governance

2.1. Present Situation of Safety Management of Distribution Network

At present, the distribution network is in a critical stage of transition from "passive" to "active" [4]. On the one hand, the infrastructure of distribution network has been continuously improved, the coverage rate of smart meters has been greatly improved, and distribution automation systems have been applied in major cities across the country, realizing real-time monitoring and basic control of the operation status of key nodes. On the other hand, in order to meet the growing demand for power quality, the traditional safety management mode mainly relies on "experience-driven" and "passive response", that is, after the fault occurs, the fault is isolated by the action of protective devices, and it is restored by manual inspection or simple automation system. With the deep integration of information and communication technology and power system, data-driven situational awareness technology began to be applied in pilot, which provided certain data support for the safe operation of distribution network.

2.2. Main Challenges Faced

(1) The double randomness of source and load leads to power flow fluctuation, and the difficulty of stability control increases sharply.

Large-scale access of distributed photovoltaic (PV), wind power and other new energy sources, as well as the wide distribution of impact loads such as charging piles of electric vehicles, make the power flow distribution of the distribution network extremely random and fluctuating [5]. The traditional one-way radial network topology is transformed into two-way power flow or even multi-terminal power supply network, which leads to the failure of the original voltage control strategy and relay protection setting coordination. Especially in the peak period of PV output or electric vehicle charging, problems such as voltage exceeding limit and line overload are easy to occur, which seriously threaten the power quality and operation stability of the system.

(2) The fault features are complicated, and there are blind spots in the traditional defense system.

With the wide application of power electronic equipment, the amplitude and phase characteristics of fault current in distribution network are distorted, showing nonlinear characteristics such as low voltage and weak feed-in. The traditional protection device based on power frequency often has the problem of insufficient sensitivity or refusal to operate when identifying high resistance grounding fault and intermittent arc fault. The connection of microgrid and energy storage equipment makes the distribution network switch between grid-connected and island operation modes more frequently. The existing fault location and isolation mechanism is difficult to adapt to this dynamic network architecture, resulting in low efficiency of fault handling.

(3) Data barriers and information islands restrict situational awareness.

Although a large number of sensors and monitoring terminals are deployed on the distribution network side, due to the lack of unified data governance standards and efficient information exchange mechanism, massive multi-source heterogeneous data are often scattered in different business systems, forming a serious "data chimney" and "information island" [6]. The existing governance methods lack the ability of deep mining and correlation analysis, and it is difficult to realize the leap from "local monitoring" to "overall situation awareness", which leads to insufficient ability to predict and warn potential security risks and cannot meet the governance needs of "prevention in advance".

(4) Under the impact of extreme external environment, the toughness of distribution network is insufficient.

Under the background of global climate change, the frequency and intensity of extreme weather and natural disasters have increased significantly. The traditional distribution network planning and design standards are mainly aimed at N-1 criterion, and lack the defense ability to deal with large-scale blackouts caused by extreme events. The weak links of the physical infrastructure of distribution network are prone to cascading failures under external shocks, and lack the ability of black start and quick recovery, which seriously affects the social livelihood and the power supply reliability of key infrastructure.

3. Empowering Mechanism of Intelligent Technology

The reason why intelligent technology can become the core engine of the power distribution network security governance capability is that it reshapes the internal logic of the four key links of "perception-analysis-decision-execution" in the traditional security governance model. Specifically, its empowerment mechanism is shown in Figure 1.

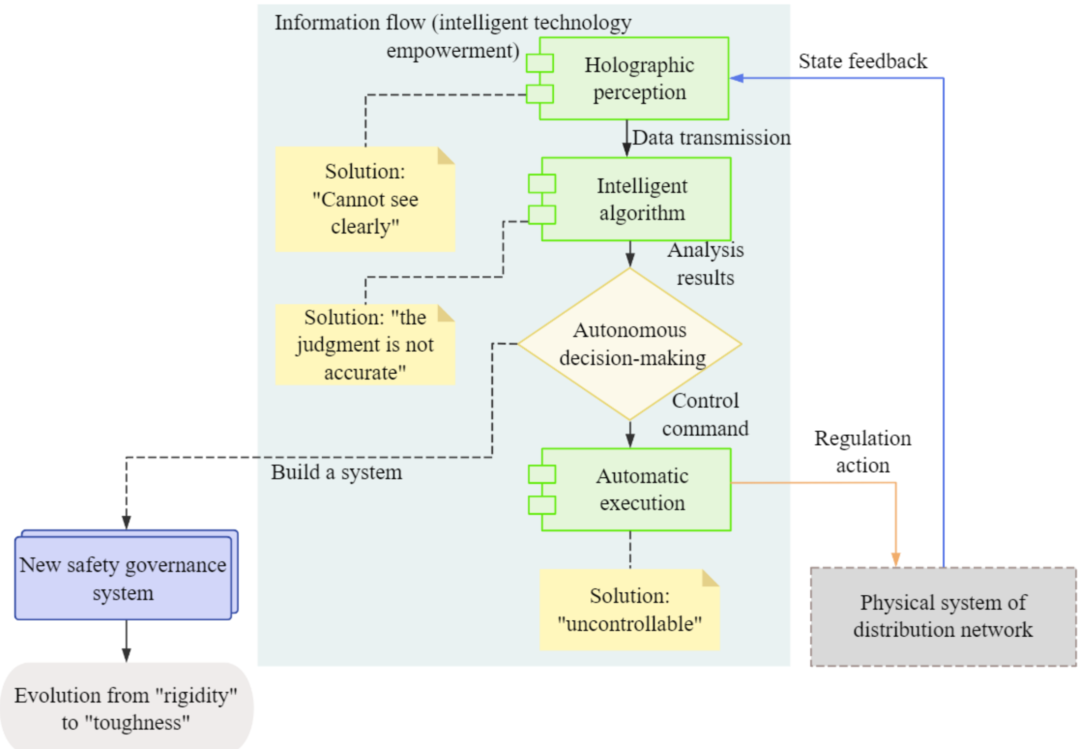

Figure 1. Empowerment mechanism framework of intelligent technology

3.1. Data-driven Panoramic Perception and State Transparency

Traditional distribution network security governance highly relies on manual inspection and post feedback, which has problems such as large perception blind spots and delayed response. Intelligent technology first achieves comprehensive and real-time collection of the operating status, equipment conditions, and environmental parameters of the distribution network through terminal devices such as IoT sensors, advanced measurement systems [7], and synchronous phasor measurement units (PMU). On this basis, the collaborative architecture of edge computing and cloud computing ensures the initial cleaning and rapid response of data locally, while uploading key data to the cloud for in-depth mining. This process breaks down the data barriers between various business systems, enabling different departments such as scheduling, operation and inspection, and marketing to share a unified data view, thereby advancing the time window for identifying security risks from "after the accident" to "the budding stage of hidden dangers" and achieving a proactive warning transformation.

3.2. Accurate Diagnosis and Situation Deduction Based on Algorithm Empowerment

On the basis of obtaining holographic data, the core value of intelligent technology lies in using AI algorithm to replace or assist the human brain in complex causal reasoning and trend prediction. Specifically including:

1) Abnormal detection and fault location. Using deep learning to learn historical fault waveforms and normal working condition data, a high-precision fault identification model is constructed. When complex faults such as single-phase grounding and arc discharge occur in the distribution network, the model can automatically identify the fault type and accurately lock the fault point within a few seconds, which greatly shortens the time of traditional manual line inspection.

2) Risk assessment and dynamic early warning. Combined with meteorological data, load forecasting data and equipment aging model, the vulnerability of distribution network in a specific period of time in the future is dynamically evaluated by reinforcement learning or Bayesian network.

3) Situation deduction and optimal decision. Based on the digital twin platform, operation and maintenance personnel can simulate the evolution process of power grid in various extreme scenarios. Through rapid iterative calculation, the AI algorithm recommends the optimal control strategy with both safety and economy, and upgrades the decision-making basis from personal experience to scientific conclusions supported by data and algorithms.

3.3. Self-healing Control and Agile Response Supported by Intelligent Terminal

The ultimate goal of security governance is implementation. Intelligent technology realizes millisecond release and closed-loop execution of control instructions through the deep integration of automation terminal and communication network. When there is a permanent fault in the distribution network, the feeder automation system based on local control or centralized control of the main station can automatically isolate the fault zone and quickly restore the power supply in the non-fault area through the automatic switching of the contact switch. The entire process does not require manual on-site operation, compressing the power outage time from hours to seconds or even milliseconds. In response to the randomness and volatility of distributed PV, energy storage, and charging stations, intelligent technology uses virtual power plant (VPP) aggregation technology to uniformly schedule these dispersed resources [8]. When the local voltage exceeds the limit or the transformer is overloaded, the system will automatically issue instructions to adjust the reactive power output of the inverter, reduce the charging power or start the energy storage to cut the peak and fill the valley, so as to realize the dynamic balance of the source network and the automatic satisfaction of the security constraints.

4. Path Construction of Improving Safety Governance Capacity

4.1. Technology Empowerment

Technology is the core engine to improve the ability of safety governance. It is necessary to focus on the pain points in the whole process of distribution network operation, build an intelligent technology system covering perception, analysis and disposal, and open up the technical closed loop of safety governance. On the one hand, relying on intelligent sensing technology to realize the global visualization of distribution network operation status, by deploying high-precision sensors and intelligent terminals, real-time collection of key information such as distributed power output, line operation parameters, equipment health status, etc., combined with edge computing technology to realize the localization pretreatment of data, eliminate the blind spots and lag of traditional sensing, and provide accurate data base for security management; On the other hand, with intelligent analysis and decision-making technology as the core, a distribution network security situation awareness platform is built, and AI algorithms are used to deeply mine massive operating data, achieving early warning of potential faults and accurate identification of fault types. At the same time, relying on intelligent scheduling and self-healing technology, a rapid fault disposal mechanism is constructed. When there is an abnormality in the distribution network, the system can automatically generate the optimal disposal plan, drive equipment to act autonomously, greatly shorten the fault disposal time, and improve the self-healing ability and resilience of the distribution network [9]. In addition, strengthening the deep integration of intelligent technology and physical systems of distribution networks, promoting the transformation of traditional distribution networks into digital twin distribution networks, and constructing virtual images of physical distribution networks to achieve real-time mapping and dynamic inference of operating status, anticipate potential safety risks in advance, and provide forward-looking decision-making support for safety governance.

4.2. Management Innovation

Technical empowerment needs to resonate with management innovation at the same frequency in order to fully release governance efficiency. It is necessary to rely on intelligent technology to promote the transformation of distribution network security management mode from extensive and empirical to refined and intelligent, and to build a management system that adapts to the operating characteristics of intelligent distribution network. First of all, reconstruct the organizational structure of safety governance, break the information barrier between traditional departments, establish a cross-departmental and cross-disciplinary collaborative governance mechanism, and rely on the intelligent collaborative management platform to realize information sharing and joint disposal of operation and maintenance, scheduling, marketing and other departments, to ensure the rapid transmission of safety governance instructions and clear implementation of responsibilities, and improve the efficiency of collaborative disposal; Secondly, optimize the safety governance process, embed intelligent technology into the whole process of fault investigation, hidden danger management, emergency treatment, etc., and rely on the digital process management system to realize the standardization and transparency of the governance process, reduce the uncertainty caused by human intervention, and establish a closed-loop management mechanism based on data. By tracking and analyzing the data of the governance process, the governance process is continuously optimized and the management accuracy is improved; Furthermore, strengthen personnel capacity building, carry out special training around the application of intelligent technology, cultivate a compound talent team that not only knows the professional knowledge of distribution network, but also masters the skills of intelligent technology, establish an assessment and incentive mechanism that matches intelligent governance, incorporate the application effect of intelligent technology into the assessment system, and stimulate the initiative and creativity of personnel to use intelligent technology to carry out safety governance, thus providing a solid talent guarantee for safety governance.

4.3. Mechanism Guarantee

Long-term mechanism is the fundamental guarantee for the continuous improvement of safety governance capacity. It is necessary to build an institutional norm and guarantee system that adapts to the driving characteristics of intelligent technology to provide solid support for technology empowerment and management innovation. On the one hand, improve the standard and specification system, combine the operation characteristics of smart distribution network with the safety governance requirements, formulate technical standards and management specifications covering smart equipment access, data collection and transmission, safety risk assessment, emergency response, etc., clarify the boundaries and requirements of intelligent technology application, ensure that the safety governance work is rule-based and evidence-based, and avoid technical application confusion and safety risks caused by lack of standards; On the other hand, improve the coordination mechanism, strengthen the coordination between government and enterprises, promote the in-depth cooperation between power enterprises and relevant government departments in data sharing, emergency response, policy support, etc., establish cross-regional and cross-level emergency response plans, and rely on the intelligent command platform to realize the overall deployment of emergency resources and improve the emergency response capability in extreme cases; At the same time, establish a dynamic optimization mechanism, combine the actual operation of distribution network with the development of intelligent technology, regularly evaluate and iterate the safety governance path, technical scheme and management system, timely adjust the shortcomings of the mechanism that are not suitable for the development of intelligent distribution network, and ensure that the safety governance system always matches the development needs of distribution network. Strengthen the security guarantee mechanism, establish a security protection system for the application of intelligent technology, build a defense line for data security and network security, ensure the security and stability of distribution network operation data and intelligent systems, and provide a reliable security barrier for improving security governance capacity.

5. Case Analysis

In order to verify the effectiveness of the promotion path of distribution network security governance driven by intelligent technology, a typical urban distribution network demonstration area is selected for empirical analysis. The demonstration zone has a power supply area of approximately 120 km², a high load density, a total installed capacity of 45 MW for distributed photovoltaics, and over 600 electric vehicle charging stations, exhibiting typical characteristics of high penetration distributed power sources and strong random loads coexisting.

Before the treatment, the demonstration area adopted traditional manual inspection and conventional distribution automation mode. The average operation data in the past three years showed that the average fault location time was about 42 min, and the average power supply recovery time in non-fault areas was about 68 min. Power outages caused by voltage exceeding limit and line overload occur 18 times a year, and the reliability of power supply is maintained at around 99.86%. At the same time, multi-source data are scattered in three independent systems: dispatching, transportation inspection and marketing, and the average time for cross-departmental collaborative disposal is more than 30 minutes, and the situational awareness ability is obviously insufficient.

According to the empowerment mechanism and promotion path proposed in the above part of this paper, the following core measures are deployed in the demonstration area:

At the technical level, a total of 320 sets of intelligent terminals were installed to build a panoramic perception platform based on cloud edge collaboration; Deploy deep learning based fault recognition algorithms and digital twin deduction systems to achieve millisecond level anomaly detection and minute level situational assessment; Upgrade the feeder automation (FA) system to support self-healing control in collaboration with the main station on-site.

At the management level, an inter-departmental intelligent transportation and inspection center is established, and a closed-loop process of "monitoring-early warning-disposal-feedback" is established, and an intelligent collaborative management platform is developed to realize real-time information sharing; Carry out special training on AI-aided decision-making system operation for operation and maintenance personnel, revise performance appraisal indicators, and incorporate the application effect of intelligent system into quarterly assessment.

At the mechanism level, the "Technical Specification for Intelligent Terminal Access and Data Interaction" was formulated, the emergency linkage plan between government and enterprises was established, and a dynamic evaluation team was set up to iteratively optimize the governance effect every quarter.

After 12 months of actual operation, the improvement of key safety governance indicators in the demonstration area is shown in Table 1.

Table 1. Comparison of key safety governance indicators before and after governance in demonstration area

Indicator item	Mean before governance	Mean after governance
Average fault location time (min)	42.3	2.1
Average restoration time of power supply in non faulty sections (min)	68.5	8.7
Annual number of power outages for users (times)	18	4
Voltage qualification rate (%)	98.42	99.71
Average time for cross departmental collaborative disposal (min)	33.6	6.2
Advance time for risk warning (h)	0 (no warning)	4.8

In addition, the accuracy of intelligent identification algorithm for single-phase grounding fault and arc discharge fault reaches 96.7%, and the deviation between the deduced results of digital twin system under extreme working conditions and the actual situation is less than 5%. Since the system was put on line, the voltage over-limit events caused by the fluctuation of distributed power supply output have decreased by 82%, and the number of transformer overload alarms during the peak charging period of electric vehicles has decreased by 74%. The governance effect shows that the closed-loop system of "perception-analysis-decision-execution" has improved the safe operation level and fault self-healing ability of distribution network.

In order to quantify the contribution of governance in different dimensions, this study added the control group of traditional governance model on the basis of the original demonstration area, and designed the experimental scheme of separating three types of variables. The control group still uses the original manual inspection and conventional distribution automation mode, without introducing any new technology and management changes. The experimental group is deployed in three stages as shown in Table 2 below.

Table 2. Three-stage deployment

Stage	Implementation content	Corresponding variable
Stage A	Deploy only intelligent terminals and cloud edge collaborative perception platform (hardware transformation)	Technical variables
Stage B	On the basis of Stage A, establish a cross departmental intelligent operation and inspection center, and establish a closed-loop management process (management innovation)	Technical+Management Variables
Stage C	On the basis of Stage B, improve standard specifications, government enterprise linkage plans, and dynamic evaluation mechanisms (institutional guarantees)	Technology+Management+Institutional Variables

The running time of each stage is 12 months, and the improvement of key indicators is shown in Table 3 below.

Table 3. Comparison of key safety governance indicators in each stage

Indicator item	Control group mean	Stage A (Technology)	Stage B (Technology+Management)	Stage C (All variables)
Average fault location time (min)	42.3	12.5	5.8	2.1
Average restoration time of power supply in non faulty sections (min)	68.5	25.3	14.2	8.7
Annual number of power outages for users (times)	18	11	7	4
Voltage qualification rate (%)	98.42	98.95	99.38	99.71
Average time for cross departmental collaborative disposal (min)	33.6	28.1	12.4	6.2
Advance time for risk warning (h)	0	2.1	3.5	4.8

Note: The samples in each stage are all from the same demonstration area, and the operation cycle is 12 months in a row, and the sample size is not less than 365.

By comparison, it can be seen that simple technical investment (stage A) can greatly reduce the fault location time, but management innovation (stage B) contributes more significantly to collaborative disposal and recovery efficiency, and institutional guarantee (stage C) further improves the fine indicators such as early warning time and voltage qualification rate.

In order to verify the universality of the scheme, two typical scenarios are selected for comparative testing: (1) High photovoltaic penetration of township distribution network. The installed capacity of distributed photovoltaic reaches 60 MW, with low load density and long line, which is prone to voltage exceeding the limit. Focus on smart terminal coverage and digital twin deduction, and strengthen cross-village emergency linkage at the management level. The fault location time is reduced from 48 min to 3.5 min, and the voltage qualification rate is increased from 97.85% to 99.52%. (2) Distribution network of industrial park. The load is concentrated, including a large number of impact loads and sensitive users, and the requirements for power quality are extremely high. Focus on feeder automation and virtual power plant aggregation scheduling, and establish a park-level intelligent transportation and inspection center at the management level. The number of power outages decreased from 22 to 5, and the voltage qualification rate increased from 98.15% to 99.81%.

In addition to the safety indicators, the economic analysis is shown in Table 4 below. The results show that, although the initial equipment investment is large, the project can recover all the investment in about 1.7 years by saving operation and maintenance manpower and greatly reducing power outage losses, which has good economic feasibility.

Figure 2 shows the monthly change curve of fault location time in the demonstration area within 12 months. As can be seen from the figure, the indicators of the system improved rapidly in the initial stage, then entered a stable period, and the monthly fluctuation range gradually narrowed, which reflected the convergence and robustness of the governance system.

Table 4. Economic index analysis

Economic index	Before treatment	After treatment
Equipment renovation cost (ten thousand yuan)	—	480
Annual Operation and Maintenance Labor Cost (RMB 10,000)	320	185
Annual power outage loss (ten thousand yuan)	560	120
Payback period of investment (year)	—	1.7

Note: The power outage loss is converted according to the local industrial and commercial average electricity price and power outage duration, and the labor cost of operation and maintenance includes patrol inspection, emergency repair and dispatching.

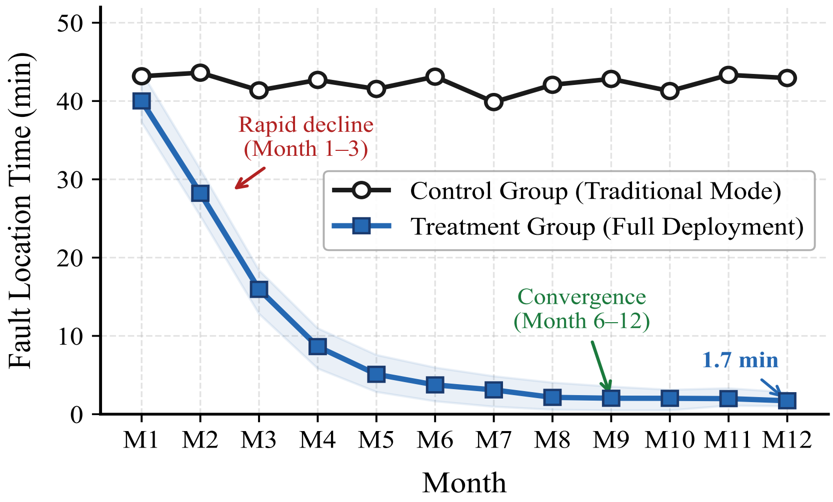

Figure 2. Monthly change curve of 12-month fault location time

6. Conclusion

By reshaping the closed-loop logic of "perception-analysis-decision-execution", intelligent technology has become the core engine to drive the leap of governance capacity. In this paper, a systematic promotion path covering technical empowerment, management innovation and mechanism guarantee is constructed. Technically, an intelligent technical system covering perception, analysis and disposal is constructed to promote the digital twin transformation of distribution network. In management, through restructuring the organizational structure and optimizing the governance process, cross-departmental collaboration and refined management and control are realized; In terms of mechanism, we should improve the standard specification and collaborative linkage mechanism, and establish a dynamic optimization and security system. The governance path driven by intelligent technology breaks the data barrier, improves the self-healing ability and operational toughness of distribution network, and provides theoretical support and practical guidance for building a highly reliable modern distribution network.

References

[1] Dhasagounder, M., & Kaliannan, J. (2026). Application of computational intelligence techniques for frequency stabilization in isolated microgrid systems. International Journal of Applied Electromagnetics and Mechanics, 80(7), 263–282. https://doi.org/10.1177/13835416261449033

[2] Song, Q., Sheng, W., Kou, L., et al. (2016). Smart substation integration technology and its application in distribution power grid. CSEE Journal of Power and Energy Systems, 2(4), 31–36. https://doi.org/10.17775/CSEEJPES.2016.00046

[3] Avcı, E. (2024). Hybrid Artificial Intelligence Techniques for Enhanced Electricity Outage Prediction and Management in Distribution Networks. Turkish Journal of Electrical Power and Energy Systems, 4(2), 63–73. https://doi.org/10.5152/TEPES.2024.24008

[4] Naily, E. N., Saad, M. S., Hussein, T., et al. (2017). Minimizing the impact of distributed generation of a weak distribution network with an artificial intelligence technique. Applied Solar Energy, 53(2), 109–122. https://doi.org/10.3103/S0003701X17020128

[5] Oriza, C., Abdeljelil, C., I. M, A., et al. (2023). Optimal energy scheduling of the smart stand-alone electrical distribution grid considering power-to-gas storage technology and reserve strategy. Electrical Engineering, 106(2), 1939–1958. https://doi.org/10.1007/S00202-023-02041-9

[6] Bai, J. (2026). The Application Progress of Artificial Intelligence Technology in The Optimal Dispatch of Smart Grids. Frontiers in Computing and Intelligent Systems, 16(1), 139–145. https://doi.org/10.54097/SXFKV686

[7] Sarkar, S., Chakrabarti, U., Bhattacharyya, S., et al. (2020). A Comprehensive Assessment of the Need and Availability of Smart Grid Technologies in an Electricity Distribution Grid

Network. Journal of The Institution of Engineers (India): Series B, 101(6), 1–9. https://doi.org/10.1007/s40031-020-00486-1

[8] Farshid, S., Nikhil, K., & K. A, S. (2017). Optimal Control Algorithms for Reconfiguration of Shipboard Microgrid Distribution System Using Intelligent Techniques. IEEE Transactions on Industry Applications, 53(1), 474–482. https://doi.org/10.1109/tia.2016.2601558

[9] Sara, M., Danny, P., & Goran, S. (2017). Strategic Distribution Network Planning With Smart Grid Technologies. IEEE Transactions on Smart Grid, 8(6), 2656–2664. https://doi.org/10.1109/tsg.2016.2533421